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OWER DISTRIBUTION NETWORKS WITH THE MAXIMAL NEARBY LOCATION OF TRANSFORMER SUBSTATIONS TO CONSUMERS

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Abstract: *The article considers the feasibility of changing the structure of a distribution electrical network by transferring points of electricity transformation as close to consumers as possible. This approach is based on installation of pole-mounted transformer substations (PMTS) near consumer groups and changes the topology of the electrical network. At the same time, for groups of consumers, the configuration of sections of the low-voltage network, including service drops, changes. The efficiency of approaching transformer substations to consumers was estimated by the reduction in electrical energy losses due to the expansion of the high-voltage network. The calculation of electrical losses was carried out according to twenty-four hour consumer demand curve. To estimate the power losses in each section of the electrical network of high and low voltage, the calculated expressions were obtained. For the considered example, the electrical energy losses in the whole network with a modified topology is reduced by about two times, while in a high-voltage network with the same transmitted power, the losses are reduced to a practically insignificant level, and in installed PMTS transformers they increase mainly due to the rise in total idle losses. The payback period of additional capital investments in option with modified topology will be significantly greater if payback is assessed only by saving losses cost. Consequently, the determination of the feasibility of applying this approach should be carried out taking into account such factors as increasing the reliability of electricity supply, improving the quality of electricity, and increasing the power transmission capacity of the main part of electrical network.*

Keywords: *power distribution network; electrical energy losses; quality of electricity; power transmission capacity; reliability of electricity supply; energy conservation; feasibility study; pole-mounted transformer substations.*

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РАСПРЕДЕЛИТЕЛЬНЫЕ ЭЛЕКТРИЧЕСКИЕ СЕТИ 10/0,4 КВ С МАКСИМАЛЬНЫМ ПРИБЛИЖЕНИЕМ ТРАНСФОРМАТОРНЫХ ПОДСТАНЦИЙ К ПОТРЕБИТЕЛЯМ

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Резюме: *В статье рассматривается целесообразность изменения структуры распределительной электрической сети путем переноса пунктов трансформации электроэнергии как можно ближе к потребителям. Такой подход опирается на установку* *вблизи групп потребителей столбовых трансформаторных подстанций (СТП) и меняет топологию электрической сети. При этом для групп потребителей изменяется конфигурация участков сети низкого напряжения, включающих вводы в дома и здания. Эффективность приближения трансформаторных подстанций к потребителям оценивалась по величине снижения потерь электроэнергии за счет расширения сети высокого напряжения. Расчет потерь электроэнергии был выполнен по часовым интервалам типового суточного графика нагрузки потребителей. Были получены расчетные выражения, позволяющие вычислить потери мощности на всех участках электрических сетей низкого и высокого напряжения. Для рассмотренного примера потери электроэнергии в целом по сети с измененной топологией снижаются примерно в два раза, при этом в сети высокого напряжения с прежней передаваемой мощностью потери снижаются до практически незначимого уровня, а суммарные потери в трансформаторах возрастают в основном из-за роста общих потерь холостого хода. Срок окупаемости дополнительных капитальных вложений в вариант с изменённой топологией будет достаточно большим, если окупаемость будет оцениваться только за счет экономии при снижении потерь. Определение целесообразности применения данного подхода следует производить с учётом таких факторов, как увеличение надёжности электроснабжения, повышение качества электроэнергии и увеличение пропускной способности магистральной части электрической сети.*

Ключевые слова: *распределительная сеть; потери электроэнергии; качество электроэнергии; пропускная способность; надежность электроснабжения; энергосбережение; технико-экономическое обоснование; столбовая трансформаторная подстанция.*

Introduction

The problem of high energy losses and low voltage levels in low-voltage distribution networks (secondary distribution networks) is discussed in many publications, for example [1-3]. To solve this problem, well-known methods are used [4, 5], namely: replacing overhead line (OHL) wires with larger cross-section wires, disaggregation of lines, reactive power compensation and installation of control transformers. The transfer of electrical network to a higher rated voltage for low-voltage networks is not applied, since power receivers are connected directly to this network.

For suburban and rural networks, overhead lines are used, which account for the majority of the load losses. Load losses also occur in a step-down transformer of a transformer substation (TS) and inputs to houses and buildings. Transfer to a higher rated voltage in such networks is possible on the sections of the overhead line and on branches from it when moving the transformation closer to consumers using pole-mounted transformer substations (PMTS). This approach is used in many countries, in particular the USA and Canada [6, 7], where three-phase distribution (12.47/0.416 kV) and single-phase (7.2/0.24 kV) transformers are usually installed near consumers.

In the Russian literature, there appear proposals for the use of the so-called innovative network in which pole-mounted transformer substations (PMTS) are as close to the consumer as possible [8, 9]. The innovative project of Rosseti[1] considers the use of 6–10/0.4 kV PMTS with capacities from 25 to 100 kVA, installed in close proximity to consumers and allowing one to minimize the length of 0.4 kV OHL. The project aims to increase the reliability of electricity supply to consumers through the use of simpler design solutions: the use of PMTS installed on

[1] Innovation and evolution. Rosseti // Electrical energy. Transmission and distribution. 2017

standard supports; replacement of disconnectors and fuses by reclosers installed on branches from OHL 10 kV lines and ensuring their protection up to PMTS installed.

For electrical networks of external power supply with a voltage of 0.4-10 kV for agricultural purposes, the new construction is recommended to be carried out by transferring transformation points (several PMTS 10/0.4 kV with a capacity of up to 40 kV·A with single-phase and three-phase transformers) directly to the consumer.

The benefits of PMTS using near consumers are:

- Improving the quality of electricity at the consumer;
- Reduction of electricity load losses;
- Reduction of commercial electricity losses;
- Reduction of operating costs;
- Simplification of the installation of automated electricity metering;
- Simplification of the installation of protective equipment;
- Increasing the transmitting capacity of main OHL;
- Improving the reliability of power supply.

We should also note the following disadvantages of expanding the 10 kV network, replacing the 0.4 kV network:

- Increasing the OHL cost;
- Increasing the total cost of distribution transformers;
- Increasing the idle losses.

The feasibility study of the new network topology can give various results, which are determined by the specifics of consumers' location, their capacity and daily load schedules, as well as by the lengths of the main line and branches from it. PMTS power and the number of consumers connected to them are also of importance.

Materials and methods

Consider one approach to justifying a project to build a 10/0.4 kV electrical network with TS transfer as close to electricity consumers as possible.

To justify this approach, we adopt a method for comparing network construction variants.

New construction can be performed in 2 options:

Option 1. The network is constructed by steel insulated wires (the Russian SIP type) at a voltage of 0.4 kV. The cost of TS is included in the capital investment of the option (traditional option).

Option 2. The network is constructed by protected wires (SIP3) at a voltage of 10 kV with PMTS being placed near a group of consumers (1-6 and more) and inputs into buildings at a voltage of 0.4 kV. There is no centralized TS, and a new 10 kV line connects to the existing 10 kV network.

For simplicity, we assume that consumers have the same power and the same configuration of the daily load schedule, the main line does not have branches and consumers are evenly distributed along the main line on both sides of it, and the length of the inputs to them from one support on both sides of the main line is the same.

As a comparison criterion, we take the total discounted costs for the eight-year life of the facility. Schemes of the options are shown in Figs. 1 and 2.

We accept the cost of construction of 1 km of 0.4 kV OHL with SIP2 wires 3x50+1x54.6 - 1200 ths. rubles, and for 10 kV OHL with SIP3 50 wires - 1885 ths. rubles[2]. Given the market cost of 4 PMTS with transformers of 25 kV·A and TS with a transformer of 100 kV·A, as well as the cost of SIP4 wires 2x25 for inputs to buildings, we get the cost of constructing 0.4 and 10 kV network options, respectively, 1103 and 1654 ths. rubles.

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[2] Integrated price standards for typical technological solutions for capital construction of electrical power facilities in terms of electrical grid facilities. Approved by order of the Ministry of Energy of Russia dated February 8, 2016 No. 75.

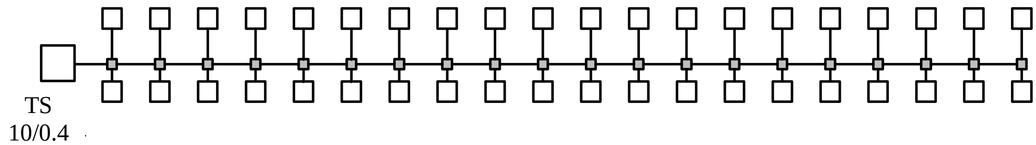

Fig. 1. Scheme of the 0.4 kV network option

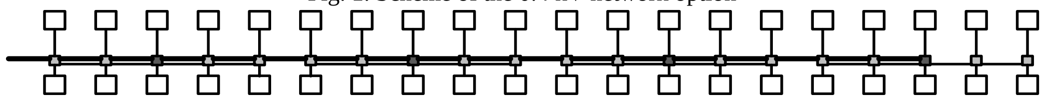

Fig. 2. Scheme of a 10 kV network option using PMTS (version with 10 consumers at PMTS). The supports on which the PMTS are mounted are indicated by dark gray.

Electricity losses ΔW for the two options are determined using the formula:

$$\Delta W = \Delta W_{OHL} + \Delta W_{in} + \Delta W_T + \Delta W_{idle},$$

where ΔW_{OHL} is the losses in overhead line; ΔW_{in} is the losses for inputs to buildings; ΔW_T is the load losses in transformers; ΔW_{idle} is the losses of idling in transformers.

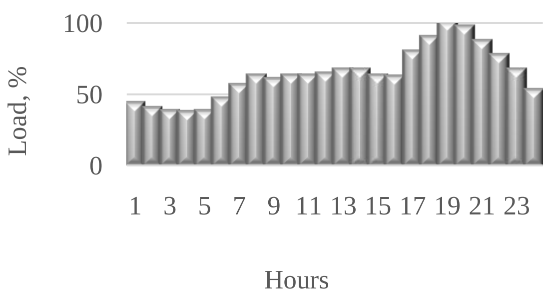

Fig. 3. A twenty-four hour load chart for private houses

A significant share of power losses for a low-voltage network occurs in the OHL network sections, for example, according to [10], losses in OHL are 91.8%, and at inputs (connections) of consumers it is 8.2%. Therefore, by changing OHL to 10 kV voltage can have a very large impact on reducing line losses.

A 10 kV OHL with a function of power distribution to consumers with PMTS will be characterized by low load and low current density. Replacing a 0.4 kV line with a maximum current of about 200 A at the head section (current density of about 4 A/mm^2) with OHL of 10 kV, we have a 25-fold decrease in current and current density (with the same wire section): 0.16 A/mm^2, which entails a huge reduction in power losses: 25^2 times. The load losses in such OHL become negligible. It is natural to believe that a 10 kV network can and should cover much more consumers and it should be used where 2 or more TS are using a traditional power supply scheme with a 0.4 kV network.

For numerical estimation of losses reduction, we compare losses in the schemes shown in Figs. 1 and 2. To calculate the losses, we take the daily schedule of the private houses load shown in Fig. 3.

The monthly electricity consumption of a residential building in which three people live can be taken 470 kWh, therefore, the average power consumed by one house is: Pav=0.654 kW. Assuming that the daily load schedule of one month is the same for all days of the month, we get the average power equal to 63.4%, so the schedule fill factor β=0.634 and the maximum power Pmax=1.03 kW. It should be noted that the considered load shedule refers to the total power of the line, and for each house individually or several houses, the fill factor will be less, and the energy losses in the OHL end sections and at the inputs will be more. For simplicity, we accept the same schedule for all parts of the network.

Losses calculation for networks with 0.4 kV OHL

Power losses in a single-phase input into the building at the considered time *i* are:

$$\Delta P_{in\_i}=\frac{P_i^2\left(1+\mathrm{tg}^2\varphi\right)r_{0,in}\,2l_{in}}{U_{ph}^2},$$

where P_i is the power consumed by the house during the considered hour; $\mathrm{tg}\varphi$ is the reactive power coefficient; $r_{0,in}$ is the linear resistance of the input conductor, l_{in} is the length of inputs from a certain pole; U_{ph}^2 is the network phase voltage.

Power losses in inputs to the entire building at the considered time *i*:,

$$\Delta P_{\Sigma in\_i}=n_h\Delta Pin\_i,$$

where n_h is the amount of houses.

Power losses at the OHL section *k* at the considered time *i*:

$$\Delta P_{\mathrm{sec}.OHL\,i,k}=\frac{\left\{\left[\left(P_i+\Delta P_{in\_i\,-}\right)n_i k+\sum_{m=1}^{k}\Delta P_{\mathrm{sec.\,OHL}\,i,m-1}\right]^2+\left[1+\mathrm{tg}^2\varphi\right]^2\right\}r_{0,OHL}l_{\mathrm{sec.\,OHL}}}{U^2}k_n$$

where k is the section number, starting from the furthest from TS , $\sum_{m=1}^{k}\Delta P_{\mathrm{sec.\,OHL}\,i,m-1}$ is the sum of losses at the previous OHL sections; n_i is the amount of houses connected to one PMTS; $r_{0,OHL}$ is the specific resistance of the OHL wire; $l_{\mathrm{sec.\,OHL}}$ is the length of one OHL section; U = 0.4 kV is the linear network voltage k_n = 1.2 is the non-uniformity coefficient, which takes into account the increase in power losses caused by the imbalance of the OHL phase load currents [11].

In this formula losses of reactive power for simplicity are not taken into account due to the low values of SIP inductive resistances.

OHL power losses at the considered time *i*:

$$\Delta P_{OHL,i}=\sum^{n}\Delta P_{\mathrm{sec.OHL}\,i,k},$$

Load losses in transformer at the considered time

$$\Delta P_{\mathrm{T}\,i}=\frac{\left\{\left[n_nP_i+\Delta P_{\Sigma\mathrm{B}\,i}+\Delta P_{OHL\,i}\right]^2\left[1+\mathrm{tg}^2\varphi\right]\right\}R_{\mathrm{T}}}{U_{HV}^2},$$

where R_{T} is the transformer resistance; U_{HV} is the voltage of high-voltage winding of transformer.

Daily power losses in the inputs, OHL and transformers are determined by summing 24 values of hourly power losses, the idle energy losses in the transformer is equal to the product of the idle power losses by 24 hours.

Methodology for calculating network losses with 10 kV OHL and PMTS

We accept the condition that there is a separate input for each building connected to the PMTS, while the length of the inputs for houses remote from the PMTS can be large, and neighboring supports are used to suspend them.

It is convenient to determine the power losses at the inputs to the buildings and 0.4 kV OHL, going from one PMTS in the considered hour through the average length for the inputs of one PMTS:, l_{in-av} $\Delta P_{in\_i} = n_{\text{h.PMTS}} \dfrac{P_i^2\left(1+\text{tg}^2\varphi\right) r_{0,in} 2lin\_av}{U_{ph}^2}$,

where P_i is the power consumed by the house during the considered hour; tgφ is the reactive power coefficient; $r_{0,in}$ is the linear resistance of the input conductor; l_{in_av} is the average length for the inputs of this PMTS; $n_{\text{h.PMTS}}$ is the amount of houses connected to one PMTS; U_{ph} is the network phase voltage.

Power losses at the PMTS transformer windings at the considered time *i*:

$$\Delta P_{Ti} = n_{PMTS} \frac{\left[\ (P_i n_{h.PMTS} + \Delta P_{in\_n})^2 (1+tg\varphi) RT\ \right]}{U_{HV}^2},$$

where n_{PMTS} is the amount of PMTS.

Transformer idle power losses are:.

$\Delta P_{Ti} = n_{PMTS} \Delta P_{idle}$.

Power losses at the 10 kV OHL section *k* at the considered time *i*:,

$$\Delta P_{\text{sec.OHL } i,k} = \frac{\left[\left(P_i n_{\text{h.PTMS}} + \Delta P_{T\ i} + \Delta P_{idle}\right) k + \sum_{m=1}^{k} \Delta P_{\text{sec.OHL } i,m-1}\right]^2 \left(1+\text{tg}^2\varphi\right) r_{0,OHL} l_{\text{sec.OHL}}}{U^2},$$

where $l_{\text{sec.OHL}}$ is the length of the 10 kV section between two PMTS; U =10 kV is the linear OHL voltage.

OHL power losses at the considered time *i*:. $\Delta P_{OHL} = \sum_k \Delta P_{\text{sec.OHL } i,k}$.

Daily power losses in the inputs, OHL and transformers are determined by summing 24 values of hourly power losses, the idle energy losses in the transformer is equal to the product of the idle power losses by 24 hours.

The following values are taken in the calculations [12]: the linear resistance of the SIP2 wire is 3x50+1x54.6: 0.641 Ohm/km, the linear resistance of the SIP-3 wire 50 is: 0.72 Ohm/km, the linear resistance of the SIP-4 wire 2x25 is: 1.2 Ohm/km

Active resistances of transformers [13]:

TMG-100/10: $R_{\text{T}} = \dfrac{P_\kappa \cdot U_{rat}^2}{S_{rat}^2} = \dfrac{1970 \cdot 10^2}{100^2} = 19{,}7 Ohm$

TMG -25/10: $R_{\text{T}} = \dfrac{P_\kappa \cdot U_{rat}^2}{S_{rat}^2} = \dfrac{600 \cdot 10^2}{25^2} = 96 Ohm$

Results

For the first option, losses in the network with 0.38 kV OHL (Fig. 1) amounted to 31.83 kWh (4.83% of the transmitted energy); for the second option, the losses in the network with 10 kV OHL and PMTS (Fig. 2) amounted to 15.7 kWh (2.44% of the transmitted power). Thus, losses decreased by 2 times when using a network with PMTS. The structure of losses is shown in Figs. 4 and 5.

The payback period of the option with large capital investments (10 kV network) will be long enough if the payback is estimated only by saving losses. Approximately accepting annual electricity losses as daily losses multiplied by the number of days in a year, for the given example, additional capital investments in the second option will pay off by saving losses for 31 years. At the same time, taking into account an increase in the reliability of power supply, an increase in the quality of voltage among consumers, as well as a number of other indicators, the electrical network of 10 kV should be considered more preferable. A similar assessment is given by the authors [14], arguing that such reconstruction or new construction provides significant savings in network losses compared to any other method under consideration, but the initial high investment outweighs the benefits offered for the remaining part of the evaluation period.

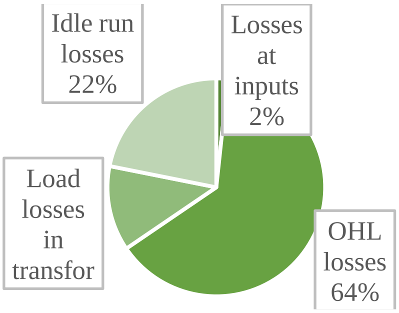

Fig. 4. The structure of losses in the network with an 0.38 kV OHL with the head TS

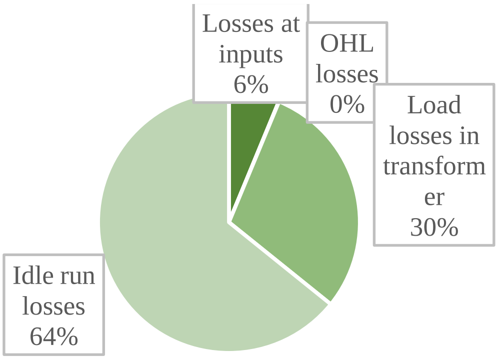

Fig. 5. The structure of losses in the network with an 10 kV OHL with PMTS

Calculations of electrical energy losses made for cases of installation of 5, 6, and 8 PMTS (the number of connected houses to one PMTS, respectively, are 8, 6, and one PMTS with 4 houses and 5) showed an increase in losses with an increase in the number of PMTS. Since that losses for a 10 kV network are determined only by losses in transformers (Fig. 5), with a decrease in the load per one PMTS (number of houses), the total load losses in transformers decrease, while the total idle losses increase as the number of transformers increases. In this case, idle run losses prevail over load losses, and the total losses in transformers increase.

Comparing the economic efficiency of construction of distribution networks using PMTS in Russia and North America, where such networks are widespread, it is worth noting that in Russia the cost of electricity for the population is about two times lower than in the United States. And the energy consumption by one house in the USA is 897 kWh [15], which is almost twice as much as in Russia.

Conclusions

1. In an electrical network with PMTS located as close to the consumer as possible, the losses in medium-voltage OHL become insignificant, while the losses in PMTS transformers increase. In general, losses are mostly reduced.

2. The more consumers (houses) are connected to one PMTS, the lower the total power losses in the transformers and in the network as a whole are, while losses at the inputs increase due to an increase in their length.

3. The rationale for building a network with PMTS as close to the consumer as possible cannot be done taking into account only the reduction of electrical energy losses in the network; one should evaluate the improvement of electrical energy quality, the reliability of power supply and the reduction of operation costs. Improving the quality of electrical energy, first of all, will affect the reduction of negative voltage deviation among consumers, as well as the voltage asymmetry coefficient in the zero sequence. It should be expected that an increase in the reliability of power supply will occur due to a decrease in the failure rate of a total network of 10/0.4 kV, by switching off only PMTS with damaged sections of the 0.4 kV network, as well as due to a higher level of 10 kV OHL reliability as compared to 0.4 kV OHL.

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